

An Investigation on Cooling of CZT Co-Planar Grid Detectors

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Abstract

The effect of moderate cooling on CdZnTe semiconductor detectors has been studied for the COBRA experiment. Improvements in energy resolution and low energy threshold were observed and quantified as a function of temperature. Leakage currents are found to contribute typically ~ 5 keV to the widths of photopeaks.

Key words: CZT, CdZnTe, CPG, Co-Planar Grid, COBRA, double beta decay, energy resolution, threshold

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1 Introduction

In recent years a lot of effort has gone into the understanding of new semiconductor materials. There is much industrial and scientific interest in the development of Cadmium Zinc Telluride (CZT) detectors because of their high stopping power and room temperature operation. Such devices have a wide field of application in hard X-ray/ γ -ray astronomy, medical imaging applications and general radiation detection like dosimetry.

A novel application is their usage to search for rare nuclear decays. The COBRA experiment is planning to use a large array of Cadmium Zinc Telluride (CZT) semiconductors, to search for neutrinoless double beta decays [1]. Neutrinoless double beta decay, the simultaneous decay of two neutrons inside a nucleus with the emission of two electrons only is not allowed in the Standard

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¹ COBRA collaboration: <http://cobra.physik.uni-dortmund.de>

Table 1
Double Beta Decay Isotopes present in CdZnTe

Isotope	Q-value keV
$\beta\beta$ emitters	
^{114}Cd	534
^{116}Cd	2805
^{128}Te	868
^{130}Te	2529
^{70}Zn	1001
$\beta^+\beta^+$ emitters	
^{108}Cd	231
^{106}Cd	2771
^{120}Te	1722
^{64}Zn	1096

13 Model of Particle Physics, it requires that a neutrino is its own antiparticle as
14 well as that it has a non-vanishing rest mass. For more details see [1].

15 For a double beta decay experiment, CZT offers great potential. Of the 35
16 known isotopes able to undergo double beta decay, CZT contains 5 of them
17 as shown in Table 1. Of special interest are ^{116}Cd and ^{130}Te due to their high
18 Q values.

19 Such decays would produce signals due to the combined energy deposit of
20 the two emitted electrons. Since no neutrinos are emitted in this process, a
21 peak is observed (broadened by the energy resolution of the detectors) at the
22 Q-value of each decay. The rate of these events is proportional to the mass of
23 the neutrino.

24 For decays in which neutrinos are emitted, the allowed double beta decay
25 process, the observed total energy deposits like below the Q-value, forming a
26 spectrum similar to that observed from beta decay. The experimental challenge
27 is to be able to separate the peak due to the neutrinoless mode from the
28 spectrum produced by the more frequent allowed mode. This requires a good
29 energy resolution, typically less than 2% at 2.8 MeV.

30 Additionally 4 of the isotopes can also undergo double positron decay, hence
31 emitting positrons instead of electrons ($\beta^+\beta^+$) as shown in Table 1. Although,
32 due to energy constraints only ^{106}Cd can emit two positrons, whilst the other
33 isotopes decay via mixed modes of positron and single electron capture of a
34 K-shell electron (β^+/EC) and double electron capture (EC/EC) modes.

For the modes which emit one or more positrons, the resultant signal can also comprise one or more 511 keV annihilation photons. In a large array, it is possible that the 511 keV photons will be detected a CdZnTe crystal other than the one in which the decay occurred. As each crystal signal is read-out separately this would be produce two or more coincident triggers, with known energy values in each crystal. These coincident signals are characteristic of these processes and a powerful search technique.

The energy range of the observed events span a wide range from the detection of X-rays only from double electron capture (around 60 keV for ^{106}Cd decay) up to a pair of electrons with total energy 2.8 MeV for ^{116}Cd double beta decay.

Common to all these decays is the fact that they are very rare, with half-lives well beyond 10^{20} years. For the latest COBRA results see [2]. The half-life sensitivity of the experiment is highly dependent on the energy resolution of the detectors. For the background limiting case, in which one observes no events, the lower limit on the half-life $T^{1/2}$ comes from the Poisson fluctuation on the total number of background counts observed within the peak region. The lower limit on the half-life $T^{1/2}$ (years) is:

$$T^{1/2} = \ln(2) \cdot \epsilon \cdot N_A \cdot \frac{M}{M_A} \sqrt{\frac{M \cdot t}{\Delta E \cdot B}} \quad (1)$$

where ϵ is the efficiency, N_A is Avagadro's number, M is the mass of isotope in kg, M_A is the atomic mass (kg), t is the measuring time (years), B is the background rate (events $\text{kg}^{-1}\text{keV}^{-1}\text{year}^{-1}$) and ΔE is the energy resolution (keV).

For a full-scale experiment, with which one would be sensitive to a neutrino mass of ~ 50 meV, the mass of isotope required is typically 100 kg. In such an experiment, the rate of neutrinoless double beta decays observed may be less than a few per year.

To detect such low count rates requires a detector and surrounding components of extremely high radiopurity. Shielding from cosmic rays and ambient trace radioactive backgrounds is essential. Experiments are sited underground, for COBRA in Laboratori Nazionali del Gran Sasso (LNGS, Italy). The local radioactivity is combatted using thick neutron shields and lead castles. Detectors are usually housed inside an inner ultra-clean copper shield which protects against the trace radioactivity of the lead castle. One possible large source of radioactive contamination comes from the detector electronics. For the COBRA experiment, like other semiconductor rare search experiments, the pre-amplifier electronics are placed outside the lead castle, well separated from the inner crystals. This has one obvious drawback, that the detector en-

ergy resolution is thus compromised and effectively degraded due to the long signal cable lengths needed.

Other physics searches are also possible such as the second-forbidden unique electron capture of ^{123}Te [3,5], which would produce a peak at 30.5 keV. The group has also performed measurements of the four-fold forbidden non-unique beta decay of ^{113}Cd [4] which has a Q-value of 320 ± 2 keV [11]. The shape of the beta decay spectrum is not well predicted by theory, and has only been observed by a few experiments.

To maximise the physics output of the COBRA experiment the ideal energy range observable by each subcomponent detector is between 25 keV and 3 MeV, with the best possible energy resolution.

The current COBRA incarnation is a small R&D array, designed with the aim of testing the coincident search technique. It comprises 64 CdZnTe semiconductors of 1 cm^3 organised in a $4\times 4\times 4$ array. The total mass of the experiment is $\sim 400\text{g}$. The crystal support structure is manufactured from delrin, and placed in a copper shield of 15 cm thick. The surrounding lead shield is 20 cm thick. A narrow slit in the copper shield and a V-shaped lead brick allows the detector cabling to pass through the shielding layers to the pre-amplifier electronics.

1.1 The Detectors

The COBRA crystals were supplied by EV PRODUCTS, and due to the quantity required and financial constraints, are all low-grade. The crystals were supplied without contacts; ie no wires glued to the electrodes, as all contacting methods commercially used are not sufficiently radiopure for a low background experiment. Typical methods of contacting are gluing with conductive epoxy or soldering. The crystals supplied are exactly the same in electrode design and size as those purchased pre-contacted and housed.

Techniques are sought to improve the energy resolution of this experiment whilst maintaining the low background. In this paper we consider the effect of slight cooling of the CZT detectors which could be provided by delivering cool nitrogen gas, from liquid nitrogen boil off, directly into the heart of the experiment. This would be a convenient technique since warm nitrogen gas is already delivered into the crystal housing in order to flush out radon gas.

The aim of this paper is to explore the effect of slight cooling of CZT detectors on energy resolution in general and the improvement for double beta searches specifically.

109 This work presents a systematic study of the effect of temperature on three
110 Co-Planar Grid (CPG) crystals all with size $1 \times 1 \times 1 \text{ cm}^3$ and all manufactured
111 by eV PRODUCTS, of which two were purchased uncontacted, the COBRA
112 detectors, and one which was bought commercially.

113 The CPG structure forms a virtual Frisch grid below the anode, and the
114 resulting signal is produced by electrons travelling past this virtual grid to
115 the anode. In this way there is almost no position dependence on the signal
116 amplitude and only the electron signal will be readout [6].

117 It is well known that slight cooling can dramatically reduce leakage currents,
118 and potentially enhance the observed energy resolution. Temperature effects
119 on similar sized CPG detectors have previously been reported [8,10], however
120 in these study the preamplifier electronics were also cooled. Effects on pixel
121 detectors has also been reported [9].

122 2 Experimental Setup

123 For a systematic study of CZT crystal response under slight cooling, two
124 $1 \times 1 \times 1 \text{ cm}^3$ CZT crystals with gold CPGs produced by eV PRODUCTS were
125 used. These crystals, designated A and B, were purchased for the COBRA
126 experiment and setup as follows. The two COBRA CPG crystals are seated in
127 a delrin holder, with their contacts bonded on to two Kapton cables using a
128 homemade low radioactivity conductive glue. One Kapton cable supplies the
129 HV to the cathodes, and one is for the two anode connections (see photograph
130 Figure 1). The guard rings were not connected. This is the usual manner to run
131 the detectors for the COBRA experiment as it keeps the active volume large.
132 The signal cable is $\sim 30 \text{ cm}$ long. This cable plugs in to COBRA designed
133 preamplifier and subtraction circuit electronics, based on the recommendation
134 of eV PRODUCTS

135 All preamplified signals are then shaped by an Ortec 855 shaping amplifier
136 with a shaping time of $1 \mu\text{s}$, digitised by 2048-channel MCA card, and recorded
137 by computer. The resulting spectra are analysed using ROOT peak finding and
138 continuum subtracting algorithms (TSpectrum), and the identified photopeaks
139 fitted with a two-sided Gaussian (with different rising and falling sigmas). The
140 Full Width Half Maximum is calculated using the average sigma. A full sweep
141 of all parameters; CPG balance potentiometer, grid bias and cathode voltage,
142 was made for both crystals with ^{137}Cs spectra recorded for each combination.
143 The shaping time was not optimised and remained at $1 \mu\text{s}$. The optimum pa-
144 rameters for each crystal are those settings at which the best energy resolution
145 of the 662 keV photopeak was seen at room temperature.



Fig. 1. The COBRA setup with 1 crystal. 16 crystals can be placed in to the Delrin holder. HV Kapton cable contacts to the cathode, and signal Kapton cable contacts the anodes.

The COBRA crystal holder was placed in a temperature controlled copper box, with a narrow slit to allow the Kapton cables to pass through. The copper box acts as a Faraday cage. An external peltier cooler is in close thermal contact with the exterior of the box. The thick copper walls (3 mm) produce a even thermal bath which is monitored by two temperature sensors inside. The peltier itself is cooled by a closed-loop pumped water system and cooling fans. The fan system produces a significant amount of noise which degrades the energy resolution of the detectors. Since the copper box is significantly massive, the fan system is switched off during the measurement and the temperature monitored to ensure stability during the measurement. The measurements are therefore relatively short, of 100 s duration, but are repeated to ensure repeatability. The temperature range of interest is from 2°C to 20°C.

3 Resolution Function of a Commercial Detector

All CPG detectors show a linear increase in Full Width Half Maximum with increasing energy. A possible explanation for this trend could be from the coplanar grid. Whilst the CPG design counteracts the effect of the hole-trapping in CdZnTe, the electrode design may also limit the resolution [7]. An x-y scan was made across the cathode surface of a commercial eV PRODUCTS detector with a collimated 60 keV source. The detector was a 1 cm³ detectors, bonded to eV PRODUCTS preamplifier and subtraction circuit, and housed in a cylindrical aluminium casing. We observed a systematic linear change in the photopeak position of the 60 keV line along one axis of $\sim 5\%$. This effect was first reported in [7]. Illuminating the whole cathode of the detector results in a wider photopeak due to this effect.

Another important source of resolution broadening is the fluctuation of the leakage current. For these detectors, however, we find that leakage current is

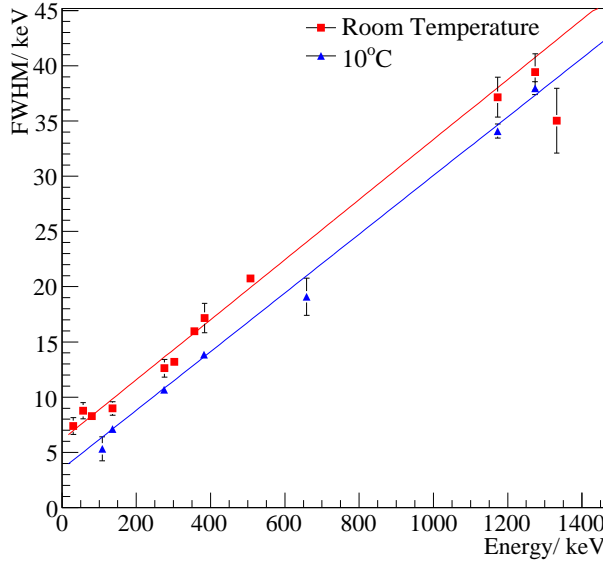


Fig. 2. Resolution Function for commercial detector at 22°C and 10°C

only significant for low energy events (below a few hundred keV).

A clear improvement was observed by cooling the commercial eV PRODUCTS detector as shown in Figure 2. This clearly shows the linear dependence of the FWHM with energy. Results are shown for measurements made at room temperature for incident gamma rays and with the entire device (crystal and pre-amplifier electronics) cooled to 10°C. Cooling this detector results in a 15% improvement at 500 keV, and a 5% improvement at 2.8 MeV. The shift downwards in intercept and overall performance improvement is interpreted as due to the reduction of bulk, surface leakage currents and electronic noise.

4 COBRA CZT Crystals

After the encouraging results from the commercial detector the COBRA crystals were cooled, with the preamplifier electronics remaining at room temperature (23°C). No spectral change was observed for the photopeaks of ^{22}Na (511 and 1254 keV), ^{137}Cs (662 keV) and ^{60}Co (1173 and 1332 keV). However, improvements were observed with ^{241}Am (60 keV) and ^{57}Co (122 keV).

4.1 Low Energy Response

Low energy spectra show a significant enhancement in resolution under cooling. Figures 3 and 4 show the spectral change observed for ^{241}Am and ^{57}Co

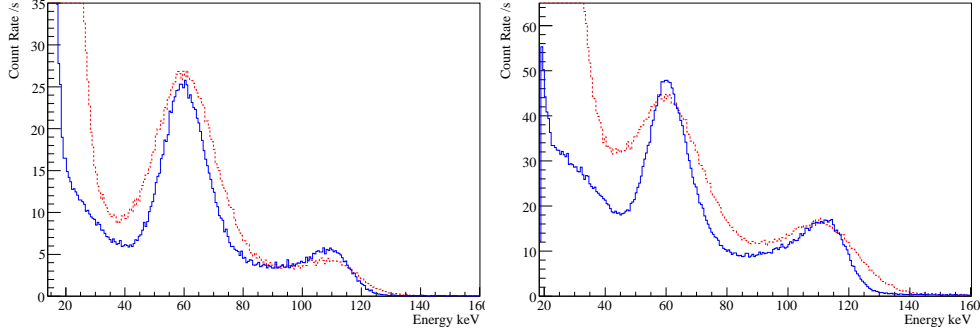


Fig. 3. ^{241}Am spectrum of crystal A (left) and B (right) at room temperature (23°C) (dashed line) and under cooling (5°C)(solid line). The feature to the right of the 60 keV peak is due to multiple events.

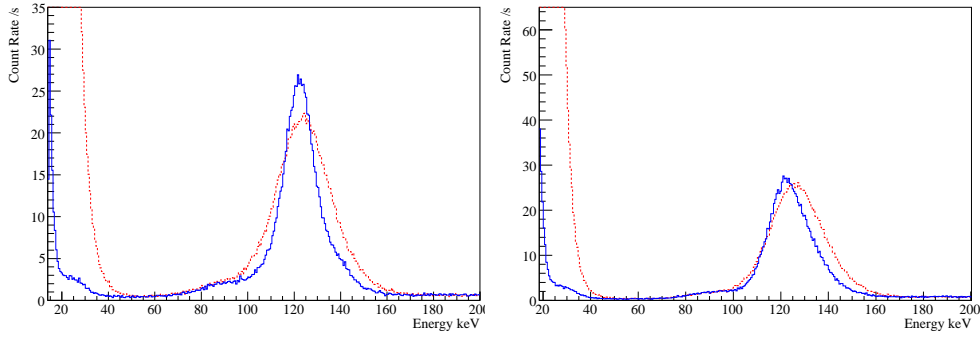


Fig. 4. ^{57}Co spectrum of crystal A (left) and B (right) at room temperature (23°C)(dashed line) and under cooling (5°C) (solid line).

190 sources cooled to 5°C . A clear improvement is observed with cooling; the pho-
 191 topeaks become narrower such that other spectral features become visible. In
 192 addition, the low energy threshold drops such that features at 30 keV become
 193 apparent.

194 Measurements of the FWHM of the 122 keV line from ^{57}Co and the 60 keV line
 195 from ^{241}Am were made as a function of temperature for the two crystals, and
 196 are shown in Figures 5 and 6. The sources were not collimated and the cathodes
 197 of both detectors were equally illuminated. Both data sets are fitted by a single
 198 exponential function combined with a constant offset. The exponential form
 199 of the fitted function represents the magnitude and response of the crystal to
 200 temperature. Supporting this, the resulting fit parameters of the 60keV and
 201 122keV lines are compatible for each individual crystal, but not compatible
 202 between crystals i.e. the temperature response is a detector property.

203 The leakage current is reduced such that it is insignificant compared to other
 204 sources of photopeak broadening. For crystal A, the leakage current component

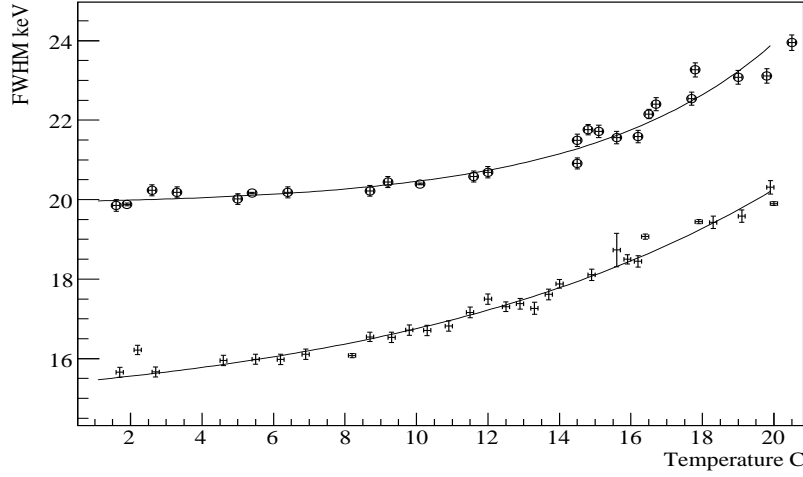


Fig. 5. Change in the FWHM of the 122 keV line of ^{57}Co as a function of temperature for crystals A(circles) and B(points). Fits to A: $(19.84 \pm 0.03) + (0.10 \pm 0.01)e^{(0.185 \pm 0.009)T}$ and B $(14.6 \pm 0.2) + (0.8 \pm 0.1)e^{(0.097 \pm 0.007)T}$.

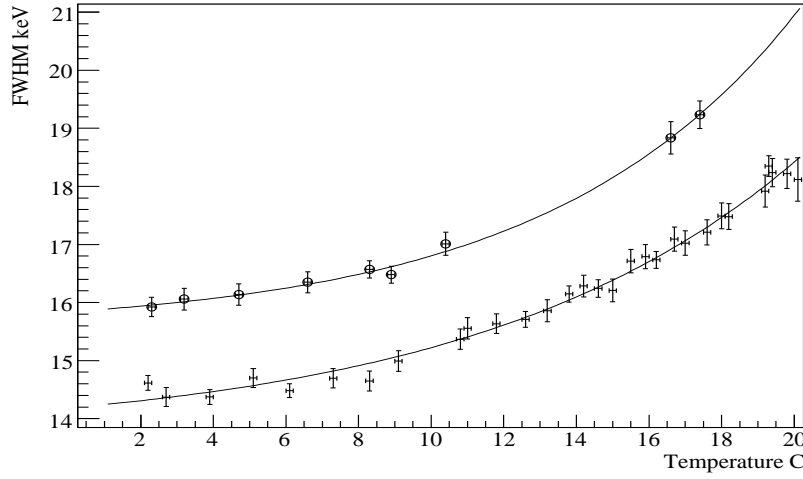


Fig. 6. Change in the FWHM of the 60 keV line of ^{241}Am as a function of temperature for crystals A(circles) and B(points). Fits to A: $(15.5 \pm 0.3) + (0.3 \pm 0.2)e^{(0.15 \pm 0.04)T}$ and B $(13.7 \pm 0.2) + (0.5 \pm 0.1)e^{(0.11 \pm 0.01)T}$

of the FWHM is $lc(T)_A = (0.10 \pm 0.01)e^{(0.185 \pm 0.009)T}$ and for crystal B $lc(T)_B = (0.8 \pm 0.1)e^{(0.097 \pm 0.007)T}$.

The residual FWHM comes from other components unaffected by temperature such as electronic noise, cable length, detector performance, and any geometrical broadening.

Cooling to 5°C brings a 25% improvement to the resolution of the 122 keV line on crystal A and 22% improvement on crystal B. For these crystals further

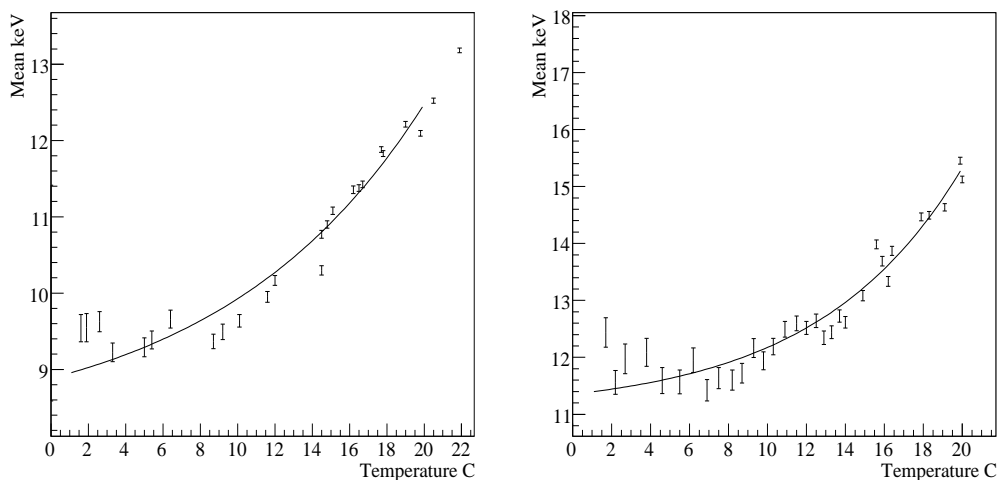


Fig. 7. Variation of the Poisson mean of the pedestal as a function of temperature from crystal A (left) and B(right).

cooling will not bring significant improvements to the energy resolution.

4.2 Low Energy Thresholds

Cooling the CZT crystals results in a significant improvement in lower energy threshold due to the reduction in leakage current, with the pedestal feature observed in the spectra clearly reducing in size. Poisson fits to the pedestal were made for spectra from both crystals for different temperatures. Figure 7 shows how the fitted mean reduces with temperature. Additionally the height of the noise pedestal also diminishes as shown in Figure 8. Similar to the photopeak resolutions, the energy threshold reaches a minimum value at $\sim 5^{\circ}\text{C}$ and further cooling does not improve the threshold.

In rare search mode, the low energy threshold is always far greater than that observed during calibrations with a high rate source. The low energy threshold can be thought of as the energy at which the noise rate drops below the real physics event rate. Low rate searches therefore experience higher low energy thresholds. Whilst it is possible to observe low energy lines ~ 30 keV during calibrations, the low energy threshold is often ~ 50 keV or higher in low background operation.

The energy threshold is therefore defined to be the energy at which the noise rate falls below a pre-determined value. Using the results of the Poisson fit to the noise pedestal (shown in Figures 7 and 8) for a particular operating temperature, one can find the energy at which the noise rate falls below a given value. For example, for a desired threshold event rate of 10^{-4} Hz at 23°C crystal A would have a low energy threshold of 37.6 keV. Lowering the

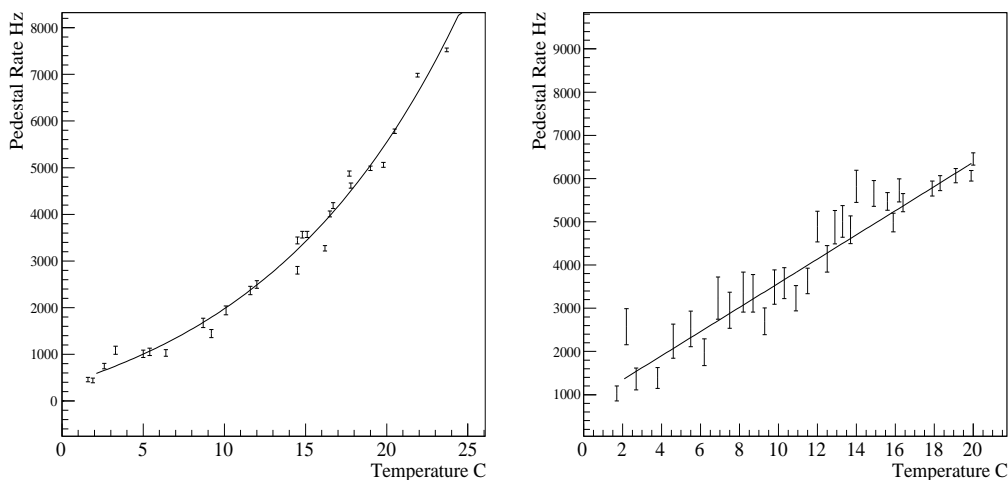


Fig. 8. Variation of the number pedestal counts as a function of temperature from crystal A (left) and B(right).

temperature to 5°C, would reduce this threshold to 29.1 keV. Similarly for crystal B, the low energy threshold would be 41.8 keV at room temperature reducing to 33.8 keV with cooling.

5 Resolution Function

Figure 9 shows the resolution functions observed with the two crystals A and B. Since no spectral change was observed for these two crystals for the higher energy lines (511 keV and above), the two straight lines above the 511 keV point represent the trend for both room temperature and under cooling. For the lower energy lines, the trends differ and the same linear trend is no longer followed. This illustrates how temperature affects the resolution function. This also shows how determining the resolution function using high energy lines and extrapolating to lower energies may result in a wrong determination of the widths of the low energy lines.

The behaviour of the resolution of the two COBRA crystals is different to that of the commercial detector, as shown in Figure2, where the room temperature and cooled resolution functions are well separated and virtually parallel. In the COBRA case there is no discernable difference between the room temperature and cooled resolution functions at 511 keV. Here the derived resolution functions merge with FWHMs of ~ 35 keV. This resolution is only reached for the highest energy lines observed with the commercial detector and we assume that for higher energy lines the resolution functions would also begin to merge.

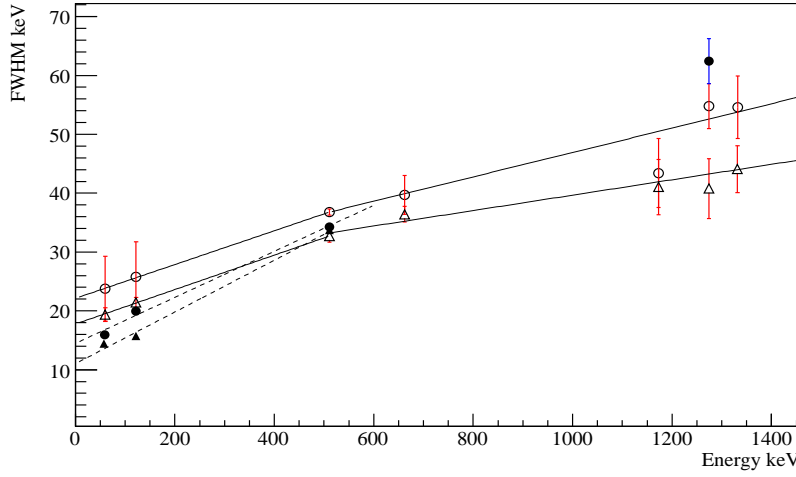


Fig. 9. FWHM versus energy for crystals A (circles) and B (triangles), open and filled markers denote room temperature and cooled data respectively. The solid lines show the trend from the 511 keV line and above. Below this the trends change, solid represents the room temperature results and the dashed line is with maximum cooling (no leakage current).

For better-performing commercial detector the leakage current is a major source of broadening across the range 60 to 1300 keV. For the COBRA detectors, the leakage current component is less important with respect to the other sources of broadening such as the electronic noise. For the COBRA detectors the electronic noise term is higher and therefore the leakage current is less significant. For energies above ~ 300 keV the leakage current is insignificant with respect to the other sources of broadening. Therefore to improve the resolutions of higher energy lines, methods to counteract this other component must be found.

6 Conclusion

A systematic study of the behaviour of two CZT Co-Planar Grid crystals under moderate cooling has been made. Significant improvements in photopeak resolution and low energy thresholds were observed. A temperature of only 5°C was found to be sufficient, below this no further improvement was observed.

The change in FWHM of photopeaks as a function of temperature was found to be well fitted by an exponential trend. For each crystal, the 60 keV and 122 keV datasets were fitted to this exponential function and the resulting fit parameters were found to be compatible, i.e. the behaviour of the photopeak resolution with temperature is the same for all energies. This is interpreted as

277 leakage current decreasing with decreasing temperature.

278 Both crystals exhibit $\sim 21\%$ and $\sim 16\%$ improvement in resolution at 60 keV
279 and 122 keV respectively under cooling. Improvements at higher energies
280 above ~ 300 keV are indiscernable, due to the insignificance of leakage current
281 broadening at these energies. The resolution here is thought to be dominated
282 by geometric and electronic effects. Typically leakage currents are found to
283 contribute ~ 5 keV to the widths of photopeaks. For these two crystals, other
284 noise sources which are not affected by the temperature of the crystal, such as
285 the electronic noise, contribute a large part of the FWHM of the photopeaks.
286 It is clear that the reduction of this contribution will be beneficial.

287 The resolution functions, trend of FWHM with photopeak energy, have been
288 determined for the commercial eV PRODUCTS detector and the two COBRA
289 detectors. They both show linear increases in FWHM as a function of energy.
290 This is interpreted as being a geometric effect, where energy depositions on
291 one side of the detector give systematically large signals than the opposing
292 side. Under cooling, the commercial detector shows improvements from 60 to
293 1300 keV. For the highest energy lines observed with the commercial detector
294 the FWHMs are ≈ 35 keV. With the COBRA detectors this FWHM is reached
295 at a lower energy at 511 keV. Above this there is no improvement seen with
296 the cooling as the leakage current is not the dominant source of broadening.

297 Moderate cooling reduces the low energy threshold due to the reduction in
298 leakage current. We consider a low background threshold event rate of 10^{-4} Hz,
299 such that the COBRA experiment operates at, and show that cooling would
300 reduce the experimental threshold of these detectors by $\sim 20\%$, to 30 and 34
301 keV for crystals A and B. We consider that cooling the crystals to 5°C of the
302 already running COBRA experiment would bring about similar improvements.
303 This would allow a search for the second-forbidden unique electron capture of
304 ^{123}Te , peak at 30.5 keV.

305 For the present COBRA experiment, mild cooling will improve the physics
306 search sensitivity to low energy lines only and will bring no improvements to
307 the search for high energy lines. However, the improvements in low energy
308 threshold increase the physics reach of the experiment.

309 To improve the resolution on the high energy lines, such as ^{116}Cd 2.8 MeV
310 line, work should focus on investigating and reducing the broadening effects
311 which are dominant at this energy. This currently appears to be due to the
312 design of the CPG grids and the pre-amplifier electronics. Future work will
313 also concentrate on reducing the electronic noise, with the aim of pushing the
314 low background threshold to well below 30 keV.

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